(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
15 September 2005 (15.09.2005)

PCT

(10) International Publication Number
WO 2005/084406 A2

(51) International Patent Classification: Not classified

(21) International Application Number: PCT/US2005/007400

(22) International Filing Date: 3 March 2005 (03.03.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/549,633 3 March 2004 (03.03.2004) US

(71) Applicant (*for all designated States except US*): **BAE SYSTEMS INFORMATION AND ELECTRONIC SYSTEMS INTEGRATION, INC.** [US/US]; 65 Spit Brook Road, NHQ01-719, Nashua, NH 03060 (US).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **ZINK, katherine** [US/US]; 15 Iron Horse Drive, Unit G207, Bedford, NH 03110 (US). **ROSSMAN, Court, E.** [US/US]; 3 Windsor Drive, Merrimack, NH 03054 (US). **LO, Zane** [US/US]; 22 Springfield Circle, Merrimack, NH 03054 (US).

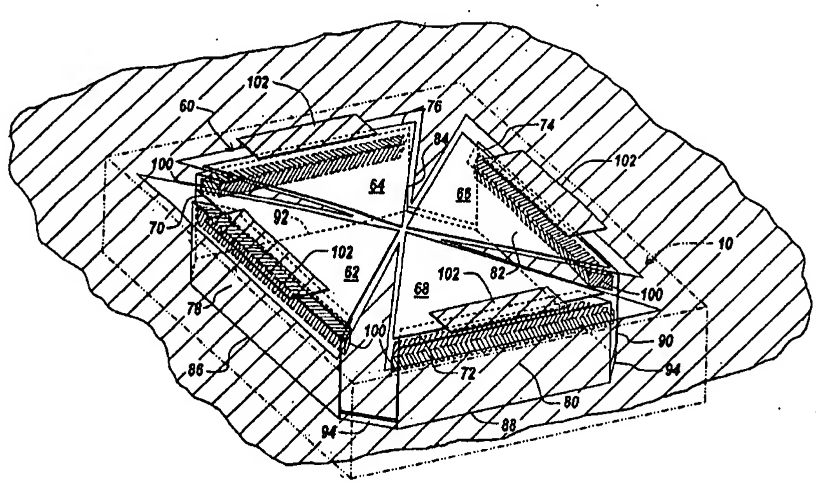
(74) Agent: **LONG, Daniel, J.**; Bae Systems Information and Electronic Systems Integration Inc., 65 Spit Brook Road, NHQ01-719, Nashua, NH 03060 (US).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO,

[Continued on next page]

(54) Title: BROADBAND STRUCTURALLY-EMBEDDED CONFORMAL ANTENNA



(57) Abstract: An embedded crossed bow tie antenna for a broad beam width and a 5:1 pattern bandwidth includes lossy material located underneath the distal ends of the bow ties to lower VSWR to below 3:1 across the entire band and to decrease nulls for more uniform antenna patterns at the high frequency end. In one embodiment, the vertical plates lower the low frequency cutoff of the antenna. DC shorting the low end of adjacent vertical plates together increases the capacitive coupling between the vertical plates and the base of the cavity to lower the low frequency cutoff and suppresses mode coupling to allow the antenna to retain its clean radiation patterns at the high end while at the same time reducing coupling between bow tie elements. In one embodiment, adding wedges of ground plane between bow tie elements reduces coupling and helps in the match and patterns at high frequencies.

WO 2005/084406 A2

SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)*

— *of inventorship (Rule 4.17(iv)) for US only*

Published:

— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

TITLE

BROADBAND STRUCTURALLY-EMBEDDED CONFORMAL ANTENNA

FIELD OF THE INVENTION

This invention relates to broadening the bandwidth and improving the high-end pattern of an electrically small, lightweight cavity embedded conformal antenna, employing a dual mode-dipole and slot-resonance.

BACKGROUND OF THE INVENTION

For airborne, high performance direction finding (DF) systems at VHF/UHF frequencies and into the microwave region, instantaneous decade bandwidth is required from the antenna. The natural way to accomplish this is to replace external antenna farms with structurally embedded, structural aperture antennas that have broadband performance.

These antennas are designed as receive-only antennas and are used for direction finding applications in which the antenna patterns need to be stable over the entire bandwidth and the patterns need a broad beam width, such as the pattern of a ground plane-backed dipole. This means eliminating nulls in the antenna pattern at high frequencies.

It is also important to have a wide bandwidth (5:1 or greater). This permits airborne receivers to detect a wide range of signals, and to be able to ascertain not only their presence and their polarization type, but also their direction and in some cases to demodulate the information on the signals.

In order to do so, one seeks to have a clean, stable pattern over the entire 5:1 band so that when doing direction finding tasks, one has a relatively constant response

for the antenna about 360° in the horizontal direction and a relatively constant pattern at depression angles from the horizontal down to immediately below the aircraft. The desired result is to have an antenna pattern which matches that of a ground plane-backed dipole in which, even at the higher frequencies, nulls are reduced as much as possible so as to have a smooth response characteristic in all directions.

Additionally, one would like to have a smaller antenna, i.e., that occupies a smaller volume, in order to install the antenna on a variety of smaller aircraft platforms without disrupting the structural integrity of the airplane.

Thus, what is required for direction-finding purposes is a miniaturized broadband antenna which has, electrically, adequate gain across the entire operating band, with a relatively low low-frequency cutoff and a relatively high high-frequency cutoff, and, which has, mechanically, a small size for structural integrity and minimal air drag.

In terms of direction finding, the simplest direction-finding antenna includes a square array on a ground plane. This is an effective standard direction finding solution where there are no scattering or aerodynamic drag constraints. A unique direction of incident radiation can be determined when the monopole separation is less than a half wavelength. Vertical monopoles or dipoles have excellent gain along the horizon due to their radiation patterns, polarization purity and efficiency.

Another way of performing direction-finding functions is to use a crossed loop variation of the four-monopole DF antenna. Again, scattering and air drag problems are significant for aircraft applications of this antenna.

In an effort to employ conformal antennas, several variations have been proposed, which antennas are flush with the ground plane and are cavity backed. Such antennas include an Archimedean spiral antenna (for circular polarization) and a

sinuous antenna (for dual linear polarization). The efficiency of these antennas is poor when the circumference is less than a wavelength, because a region of a high current resonance is never initiated at the outer circumference. The current must also travel a long distance to get to the outer edges of the antenna, further decreasing the efficiency. For the sinuous antenna, the cross polarization also dramatically increases at the low band when the radial current has as much tendency to radiate as the poorly-radiating circumferential current

A different type of cavity-backed slot antenna has been provided with a serrated edge. The serrated slot antenna has a lossy cavity behind it that has two disadvantages. The first is that the element is in the form of a patch that has no vertical walls continuing the path length. Thus, the match and radiation efficiency are reduced. Hence, the entire low frequency match is derived from the small volume of the capacitive loading at the serration, and the bandwidth and efficiency suffer as well. Additionally and more importantly, the patterns at the high end degrade and start lobing because the currents can flow undamped over the entire width of the patch. Hence, the radiation patterns are aperture limited due to the resulting side lobes.

SUMMARY OF THE INVENTION

In order to combat the above electrical and mechanical issues, a miniaturized broadband antenna has been developed with uniform and desirable antenna patterns across the entire bandwidth; involving a miniaturized cavity-embedded broadband direction-finding antenna designed with lossy material to control and stabilize the radiation patterns and to improve VSWR across the entire bandwidth.

Shorting stubs are also used to short out adjacent vertical plates. The vertical plates are used to decrease the low frequency cutoff of the antenna, with the shorting

stubs used to increase bandwidth and reduce cross-coupling at the high end of the antenna. The antenna efficiency at low frequency is increased over the spiral or sinuous embedded antennas mentioned above, with the bandwidth of the embedded bowtie in one embodiment being 5:1 that is determined by gain limitations at the low end and pattern stability at the high end.

The broad band behavior is achieved using a dual mode resonance structure of this embedded bow tie antenna; i.e., two radiation mechanisms exist, one at the low end of the band and the other at the high end of the band. At the low end of the band, radiating surface currents flow uniformly along the bow tie, and it is these dipole-mode currents that are responsible for the radiation. At the high end of the band, the power is localized to the slots, and it is the currents around these slots that are responsible for the radiation. The current flowing down the center axis of the bowtie is not as important for this radiation mechanism. Hence, the low frequency limit of the pattern bandwidth is dictated by the radiation efficiency due to the small electrical size of the embedded bowtie antenna, and the upper limit of the band is dictated by lobing in the radiation patterns as the slots and the aperture become electrically large. Given these criteria for the lower and upper limits, and a third criterion of an efficiency of 10% at the lowest frequency in the band, the bandwidth of the antenna is 5:1. At the low end of the band, the aperture is 0.13 wavelengths, which guarantees less efficiency when broadband performance is required. At the high end of the band, the aperture is 0.85 wavelengths, which allows traveling waves in the slots and pattern lobing and distortion in the undamped case.

It is desirable to ensure that currents responsible for the radiation are localized in the center of the aperture. The patterns due to radiation only from the center aperture will have the broadest beam width and bandwidth. Hence pattern stability and gain

along the horizon is improved on average over the band. The high frequency impedance behavior is that of a traveling wave antenna or transmission line. Waves traveling from the feed point towards the ends of the elements are absorbed in a lossy medium and are not reflected, providing a constant or slowly varying characteristic impedance response. Reducing the high current concentration at the corner discontinuity also maintains pattern symmetry.

The subject antenna has a number of significant features. First, the aperture is flush with the ground plane. The flush aperture eliminates air drag in military and commercial airplane applications. Secondly, the aperture is made up of a minimal number of narrow slots. The slots are designed to induce bowtie-like antenna excitations. The cavity is electrically small at the lowest frequencies of operation, and therefore requires less real estate than typical cavity antennas. In one embodiment, dual-linear polarizations can be combined for circular polarization applications or for coarse DF. Finally, the subject antenna has a 5:1 bandwidth where both patterns and match are good. This is an achievement for an antenna embedded in an electrically small cavity.

Previous designs use either a spiral or a sinuous aperture with a lossy cavity. The efficiency of these designs is poor at the low frequencies, where the outer circumference is less than a wavelength, due to no resonant mechanism for radiation.

More particularly, an embedded crossed bow tie antenna for 5:1 pattern bandwidth and match includes lossy material located underneath the distal ends of the bow ties. The lossy material is inserted to lower VSWR to below 3:1 across the entire band and to decrease nulls in the radiation pattern for more uniform patterns close to the horizon at the high frequency end. The radiation efficiency is enhanced at the low frequencies because a simple dipole resonance mechanism is enforced, similar to a

bowtie antenna, with vertical plates lowering the low frequency cutoff of the antenna. DC shorting the low end of adjacent plates together increases the capacitive coupling between the vertical plates and the base of the cavity to lower the low frequency cutoff and suppresses mode coupling to allow the antenna to retain its clean radiation patterns at the high end while at the same time reducing coupling between monopole elements

The targeted application is airborne receive-only direction finding. The closest dual-polarization competitive design, a sinuous embedded antenna, has less efficiency and polarization control at the low end of the band.

The bandwidth of the present bow tie antenna is determined, at the low end of the band, by radiation efficiency, and, at the high end of the band, by pattern symmetry and gain near the horizon. In the most conservative interpretation of this design, this embedded bowtie antenna is basically a leaky wave traveling wave antenna with the fields terminated in a broadband load starting at a quarter wave out along the slots at the highest frequency, although the resonant lengths encourage more radiation efficiency beyond this traveling wave interpretation.

The results of the design of the subject antenna are as follows. First, the fields in the slots need to be gradually absorbed starting about a quarter wave out at the highest frequency. This tapered absorber causes pattern stability and avoids radiation from traveling waves that are out of phase at the ends of the slots. This absorber termination also avoids narrow band resonant behavior, and allows good VSWR. Secondly, in one embodiment, separating the bow tie elements with a wedge of ground plane reduces coupling between these orthogonal elements, and improves VSWR and patterns at high frequencies. Thirdly, larger damping can be placed in regions of the slots, which have cross polarization currents, such as the ends of the bow tie. Fourthly, the center region of the aperture is kept free of dielectric because it is the main radiative

region. Dielectrically loaded slots do not radiate as well as unloaded air slots since dielectric traps the fields more so and the energy just uses the slots as a resistively terminated transmission line, with less radiation.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the subject invention will be better understood in connection with the detailed description in conjunction with the Drawings, of which:

Figure 1 is a diagrammatic illustration a prior art four-monopole direction-finding antenna, illustrating four upstanding monopoles;

Figure 2 is a diagrammatic illustration of a prior art cross-loop antenna for coarse direction finding;

Figure 3 is a diagrammatic illustration of a prior art Archimedean spiral antenna;

Figure 4 is a diagrammatic illustration of a prior art sinuous antenna;

Figure 5 is a diagrammatic illustration of a prior art cavity-backed slot antenna with a serrated edge;

Figure 6A is a diagrammatic illustration of a double bow tie broadband cavity-embedded flush-mount antenna, illustrating the utilization of a lossy resistive foam at the distal ends of the bow ties interior to a vertically depending plate, a resistive sheet at the distal ends of the bow ties, the utilization of a vertical plate at the distal end of the bow ties, and a mode-suppressing shunt between the bases of the vertical plates, thus to provide the antenna with adequate antenna patterns across the entire bandwidth;

Figure 6B is a diagrammatic illustration of a lossy resistive foam on both sides of the vertically depending plate of Figure 6A;

Figure 7A is a diagrammatic illustration in side view of the antenna of Figure 6A, illustrating the placement of the lossy resistive foam and the resistive sheets adjacent the slots at the distal ends of the bow ties;

Figure 7B is a diagrammatic illustration inside view of the antenna of Figure 6B, illustrating the placement of the lossy resistive foam on both sides of the vertically depending plate;

Figure 8 is a diagrammatic illustration of a top view of one embodiment of the antenna of Figure 6, illustrating a ring of absorbing material at the slots formed at the distal ends of the bow ties, an overlying resistive sheet at the distal ends of the bow ties and the utilization of a wedge of ground plane between the slots to reduce coupling and help in the match and patterns at high frequencies, the VSWR of the antenna in Figure 8 from approximately 90 MHz through 500 MHz being less than 3:1 over the entire bandwidth;

Figure 9 is a graph of the polar plots of mid-band patterns for the embedded crossed bow tie antenna of Figure 6A, illustrating close to ideal dipole patterns with minimal irregularities and side lobes, the measured frequency response of the swept gain of a single polarization yielding lower gain at the very low end of the band where 10% efficiency is tolerated, a higher-efficiency broadband peak in gain from 200 to 400 MHz, and a slow rolloff in gain from 400 to 500 MHz, as the patterns radiate more to the sides instead of at boresight; and,

Figure 10 is a diagrammatic illustration of a commercial variant of the embedded bow tie antenna of Figures 6A and 6B, illustrating the configuration used with an open cavity.

DETAILED DESCRIPTION

Referring now to Figure 1, in the prior art a four-monopole antenna 10 is shown having individual monopoles 12 vertically extending above a ground plane 14, which is used for coarse direction finding. As mentioned hereinbefore, such an antenna, while common, is not useable in airborne applications due to the fact that the monopoles are neither aerodynamically desirable, nor desirable in terms of minimal scattering.

Referring to Figure 2, a prior art crossed-loop antenna 16 is shown with crossed loops 18 and 20 above a ground plane 22 used for coarse direction-finding applications. Again, this antenna suffers from aerodynamic drag and scattering problems.

Referring now to Figure 3, in an effort to solve both the bandwidth and aerodynamic drag problems, a prior art Archimedean spiral antenna 26 is shown, with spirals 28, 30, 32 and 34 being used in a conformal patch to provide for a broadband antenna, which is mountable in a flush mount configuration. However, as mentioned before, this antenna suffers from the poor efficiency at the low end of the band.

Referring to Figure 4, a prior art sinuous antenna 36 includes sinuous elements 38, 40, 42 and 44, again presenting poor efficiency at the low end of the band.

Referring to Figure 5, a cavity-backed slot antenna 50 has a serrated edge configuration 52 which has poor pattern stability at the high end of the band.

Referring to Figure 6A, in the subject invention a cavity-embedded, dual bow tie antenna 60 is provided with opposed triangular-shaped bow tie elements 62, 64, 66 and 68 having respective distal ends 70, 72, 74 and 76. The feed points for these bow ties are labeled A, B, C and D.

Each of the bow tie elements is provided with a downwardly-depending vertical plate respectively shown at 78, 80, 82 and 84, with the respective distal ends 86, 88, 90

and 92 of the vertical plates being shorted together by a mode-suppressing shunt or short 94.

In order to lower the VSWR across the entire range of the antenna, lossy resistive foam 100 is placed beneath the distal edges 70, 72, 74 and 76 of respective bow tie elements, the insertion of which is useful in minimizing VSWR across the entire bandwidth of the antenna. In Figure 6A this materials is placed interiorly of the downwardly depending vertical plates, whereas in Figure 6B it exists on both sides of these plates. It is noted that this lossy resistive foam does not extend inwardly towards the center of the antenna so that the effective gain of the antenna is not deleteriously affected by the insertion of the lossy resistive foam.

Additionally, resistive sheets 102 are placed over the distal ends of the bow ties to further aid in the VSWR performance of the antenna.

As can be seen, the entire antenna is nested in a cavity 106, which is formed in a ground plane that in one embodiment is the conductive surface of a wing of an aircraft.

Referring to Figures 7A and 7B, in cross section, bow ties 62 and 66 are shown fed by transmission lines 110 and 112 from a coupler 114. Here it can be seen that the lossy resistive foam is positioned at the distal end 70 and 74 of respective bow ties 62 and 66 where there are large electric fields at low frequencies, i.e., interior and exterior of vertical plates 78 and 82, but immediately beneath slots 120, which are formed at the distal ends 70 and 74 of respective bow ties 62 and 66. In Figure 7A the lossy resistive foam is interior to vertical plates 78 and 82, whereas in Figure 7B the lossy resistive foam is on both sides of these plates.

Because the lossy resistive foam is limited to the distal ends of the bow ties and because it is at a position which does not have large antenna current associated

therewith, its effect on the gain properties of the antenna are minimized, while at the same time effectively reducing the VSWR of the antenna across the entire bandwidth.

Resistive sheets 102, which bridge slots 120 also aid the above-mentioned VSWR improvement.

The interposition of the lossy resistive foam and the resistive sheets also reduces side lobes at the high frequency end of the band so as to improve the antenna pattern characteristic at the high end to make the antenna an exceptionally good candidate for a direction-finding antenna at the high frequencies.

Referring to Figure 8, in which like reference characters refer to like elements between Figures 6, 7 and 8, it can be seen that the lossy foam 100 may be in the form of a foam ring below slots 120 between the respective bow ties 62, 64 66 and 68, and the surrounding ground plane generally indicated at 130. Also, as can be seen, resistive sheets 102 are positioned so as to overlie slots 120 as described above.

As can be seen by double-ended arrow 132, there is a lossless slot length that is quite large between the feed point and the point at which the bow tie encounters the effect of the lossy material, either in the form of the lossy resistive foam or in terms of the resistive sheet. Note that the lossless slot length is equal to ¼ of the wavelength at the highest frequency of the band. This being the case, there is a significant amount of lossless slot length so that the overall performance of the antenna is not impeded by the use of the resistive material.

Also shown in this figure is the extension 132 of ground plane 130 in between the bow tie elements. While there can be a single slot between the bow tie elements, when it is desired to use a significant amount of ground plane wedged between the bow tie elements, the number of slots is increased, such as illustrated by opposed slots 134 and 136 between bow tie elements 62 and 68.

The wedge of ground plane material reduces coupling and helps match and improves the antenna patterns at high frequencies.

More particularly, as illustrated in Figures 6-8, the crossed bow tie is embedded in a ground plane, forming thin slots on the flush surface. The size of the bow tie, and therefore the separation between the slots, is critical to minimizing coupling between antennas and improving radiation efficiency. As illustrated in Figure 6 it is possible to make the antenna with a single slot between the bow ties. As illustrated in Figure 8, multiple slots can be provided between bow ties.

As illustrated in Figures 6A and 6B, vertical plates 78-84 extend the respective bow ties into cavity 106. The folded bow tie approach reduces the low frequency limit of the impedance match. The vertical plates also provide capacitive loading to the cavity and further reduce the resonant frequency of the bow tie. Additionally, the additional path length provided by the vertical plates reduces multiple reflections from the ends of the horizontal elements providing a smooth VSWR response at the higher frequencies. The vertical plates are capacitively coupled to the horizontal bow tie elements for ease of manufacture.

The ends of the vertical plates are shorted together by shunts or shorts 94 to increase the capacitive loading and to act as a mode suppressor. For instance, at the higher frequencies a one-wavelength resonance on one of the bow ties can excite a cross polarization one-wavelength resonance on the orthogonal element. This short suppresses this coupling. The additional path length also reduces multiple reflections from the ends of the vertical plates and provides a smooth VSWR response.

Each bow tie is center-fed by a balanced coaxial line shown in Figures 7A and 7B by lines 110 and 112 such that the opposite halves of a bow tie are excited with equal magnitude and opposite phase. Various configurations of feed networks can be

inserted depending on the desired application. The orthogonal elements can be combined through a 90° splitter for circular polarization or through a 180° hybrid for sum and difference patterns.

A distributed lossy material, either a resistive sheet 102 or a dense foam absorber 100, is placed near or on the outer section of the bow tie. The resistive sheets of standard values below 1000 ohms/square may be insulated from the metal by a very thin spacer (not shown), with a thickness of a few thousands of an inch. If good electrical contact is made, the outer slot is simply shorted. Very poor contact between the resistive sheet and the metal will also act as a high resistance insulator.

The outer slots do not contribute to the radiation efficiency and they distort the pattern shape at the higher frequencies. Thus damping these outer slots with lossy material is helpful to insure broadband antenna performance.

As described above, distributed lossy foam is placed under the distal ends of the bow ties. This lossy foam reduces reflections from the discontinuities at the corners. In one embodiment the first 7 inches of the slot is kept free of absorber to maintain antenna efficiency. The high frequency impedance behavior is that of a traveling wave antenna or transmission line. Waves traveling from the feed point towards the ends of the elements are absorbed and not reflected, providing constant or slowly varying characteristic impedance response. Reducing the high current concentration at the corner discontinuity also maintains pattern symmetry.

It is possible to achieve a good match using loss at or close to the center feed point. This is not optimal for radiation efficiency, because the current can flow immediately into the lossy material at the high end of the band, where a traveling wave mechanism exists. At low frequencies, where a resonant mode exists, it might not matter whether the loss is placed near the feed or at the ends of the bow tie, because

damping the power anywhere on the antenna will dampen the current everywhere on the antenna. Hence, this lossy load near the feed may be appropriate if an adequate match cannot be achieved by a lossy termination at the ends of the bow tie.

The dielectric loading on the slot close to the center region of the aperture should be kept to a minimum to optimize the high band efficiency. At the high end of the receive band, when the radiation mechanism is from the slots, the slots tend to behave like slot line transmission lines, and the radiation efficiency at these higher frequencies is adversely affected by the presence of dielectric. The slot would typically be called a transmission line at these frequencies, although in this antenna these slots are being used as radiators. Radiation from transmission lines is generally less when the power and fields are trapped in a dielectric material. Note that radiation from transmission lines is the most apparent when no dielectric material is used. When the dielectric loading is large, the power travels along the slot line transmission lines and gets absorbed in the foam absorber. When the dielectric loading is small, more of the power is leaked away in the center of the aperture, as desired, when the energy travels along the slot line. In short, at the center of the antenna the slots should be free air slots devoid of dielectric.

The slot width, within limits, is not very critical for transmit efficiency. For instance, reducing the slot width from 0.030 inches to 0.015 inches does not greatly affect the antenna efficiency, although the match will change.

Rather than just placing absorbing material at the ends of the bow tie, it is also possible to duplicate the design of a resistive blade monopole and place series resistors along the bow tie. This can be accomplished by cutting very narrow slots across the bow tie and placing resistive sheets across the slots. The resistance, just as for a dipole,

increases toward the ends of the bow tie. As a result, pattern stability increases at higher frequencies.

Better efficiency at the low end can be obtained by increasing the diameter and depth of the cavity. Better efficiency can also be obtained at the low end of the band by using dielectric loading in the cavity, where this dielectric is spaced away from the slot itself. The antenna becomes more resonant, due to the better radiation efficiency, and more absorber will need to be placed at the ends of the antenna.

Antenna Performance

The focus of this particular antenna design is to provide low VSWR and wide beam widths over a 5:1 bandwidth. The pattern coverage is broad to provide direction-finding ability near the horizon. The trade-off for these characteristics is antenna efficiency, which is not the primary design driver for a receive-only DF antenna.

Lossy terminations are used to reduce the VSWR and maintain pattern symmetry without greatly affecting the system performance. The signal-to-noise ratio is dominated by ambient noise at low frequencies, below 100 MHz, so antenna efficiency is not critical.

The VSWR bandwidth of this antenna is greater than 6:1, which is greater than the useable pattern bandwidth. The measured VSWR for each bow tie pair is less than 3:1 over this 6:1 bandwidth

The VSWR for the undamped antenna is determined mostly by the tight packing between the two crossed bow ties, and the VSWR is not so much affected by the damped cavity. When the bow ties are crossed so tightly, and then they are embedded in a ground plane, an undesirable result is that the frequency-independent radiation properties are adversely affected by the reduced radiation resistance as a result of the

limited slot aperture. Instead of the radiation occurring naturally at the half wave resonance length along the bow tie, the slots act partly as transmission lines and channel the energy toward the ends of the antenna.

Because the slots act as a slot line transmission line at the high frequencies, the characteristic impedance of the slot lines has an impact on the antenna match. Slot lines do not propagate a TEM mode, and behave more like a rectangular waveguide. There exists a cutoff frequency, and the impedance goes from a large impedance close to cutoff to a small impedance at higher frequencies. Hence the match will need to be re-tuned when the gap width or metal thickness is changed.

The ground plane size has an impact on the radiation efficiency at the low end of the band, when the ground plane is less than a wavelength. Without a large ground plane the sides of the antenna can radiate, and hence the radiation efficiency is improved. With a large ground plane only the front aperture can radiate.

In one test, the subject antenna was installed on an 8-foot diameter circular ground plane and measured in a tapered anechoic chamber. Typical mid-band radiation patterns for a single polarization bow tie are shown in Figure 9. The beam width of the H plane is narrower due to the shorting effect of the ground plane around the antenna. The difference in gain at low elevations between the E and the H planes will be larger for larger ground planes.

The radiation patterns retain a similar shape to Figure 9 across the band, except for efficiency. The measured frequency response of the swept gain of a single polarization yields lower gain at the very low end of the band where 10% efficiency is tolerated due to the small size, a high-efficiency broadband peak in gain in the middle of the band, and a slow rolloff in gain from at the high end of the band, as the patterns radiate more to the sides instead of at boresight. The gain is lower at low frequencies

due to the small electrical size. The gain levels off at midband, when the diagonal slot length in the aperture is a half wavelength, and a semi-resonant radiation condition exists. It is believed that rolloff in gain at high frequencies is due to the traveling wave nature of the radiation in the slots at the higher frequencies. The frequency for the onset of the traveling wave radiation should be raised through the avoidance of dielectric loading in the slot,.

Although the antenna described was implemented for a broadband DF function, it is clear that efficiency can be improved in a narrow band design, for example, by removing some absorbing material. Other variations, including a different arrangement of slots or a different geometry of slots are also possible. Diamond or circular apertures are two examples of slot geometry variations. The slots can also be meandered to increase path length. Various absorbing terminations are also possible, such as a resistor termination to the cavity sidewalls or bottom.

Commercial applications

For commercial applications without resistive material, referring to Figure 10, higher efficiency can be achieved by relaxing the VSWR requirements, and the subject DF antenna can instead be optimized for efficiency. In a commercial DF application, the main design emphasis is to ensure efficiency at the low end of the band and pattern stability at the high end of the band. The VSWR is not critical, and a 6:1 VSWR at certain frequencies can be tolerated. Hence the efficiency of the antenna over the whole band will be larger than for an antenna optimized for VSWR.

Most importantly, to improve efficiency, the antenna slot structure can be changed. One example is shown in Figure 10. Instead of using thin slots, which can degrade the radiation efficiency, the slots can be eliminated or drastically widened as

illustrated at 140, thus creating an open cavity for the bow tie antenna. The bow tie antenna can revert back to its original broadband form. The pattern stability is much more broadband for a bow tie with an open cavity because of the large radiation resistance that naturally occurs within the quarter wave of the feed point at each frequency. Due to the high radiation resistance, the active region of the antenna is controlled by the frequency and not by the length of the slots. This is another reason that less absorber will need to be used and the antenna will be a more efficiency radiator. Minimal resistive terminations and graduated absorber may still be required for commercial aircraft DF applications to insure a consistent gain close to the horizon, and to insure an absence of pattern lobing.

When efficiency is the dominant design driver, it may be advantageous to use resonant loading on the antenna to bring the resonant frequency down, instead of broadband lossy terminations. Resonant loading is prohibitive for instantaneous broadband VSWR designs because narrow band mismatches occur. Resonant loading may take the form of meander-line connections, or cascaded ¼ wave chokes on the ends of the element.

The elements also can be fed at the ends to improve low frequency efficiency and improve vertical polarization along the horizon. The currents will be more distributed around the element and the vertical flaps can contribute to radiation efficiency. However, the pattern may start lobing at a lower frequency due to the array effect between opposite sides of the bow tie.

Direction Finding Ability:

The polarization near the horizon is predominantly vertical due to the presence of the ground plane. The radiation pattern is very similar to the pattern that would

result from a slot in the ground plane perpendicular to the bow tie element, and similar generic DF algorithms can be used. The radiation pattern is also very similar to the pattern that would result from a half wave short loop perpendicular to the bow tie element.

Due to the gain and 360-degree phase front in a circular-polarized mode (both bowtie antenna elements excited, 90 degrees out of phase), the crossed dipole antenna can be used as a coarse direction finding antenna, especially when compared to an external reference phase from a separate antenna. Without a separate external phase reference, the direction can only be determined to be one of two opposite directions. By proper combining of the outputs from the opposed bow ties it is possible to obtain coarse direction.

In contrast to a standard DF configuration of 4 monopoles, close to the same patterns are obtained when one or both sides of a single bow tie are fed with opposite phase due to the tight coupling/modal nature of the antenna excitation. The two feeds will excite close to the same currents or mode within the slots and on the metallic bow tie. When constrained to a single bow tie and with the orthogonal element not excited, as related to DF analysis, no new information is generated when switching between two feeds for the bow tie and one feed. In a standard DF configuration with 4 monopoles, it would be possible to switch between the feeds to obtain more information, because the resonance modes of each feed are separate.

While the present invention has been described in connection with the preferred embodiments of the various figures, it is to be understood that other similar embodiments may be used or modifications or additions may be made to the described embodiment for performing the same function of the present invention without deviating therefrom. Therefore, the present invention should not be limited to any

single embodiment, but rather construed in breadth and scope in accordance with the recitation of the appended claims.

WHAT IS CLAIMED IS:

1. A broadband structurally-embedded conformal antenna, comprising:

a ground plane;

an aperture in the ground plane;

a cavity opened to said aperture and extending below said ground plane;

a bow tie antenna having bow tie elements located in said aperture, the distal ends of said bow tie elements spaced from said ground plane so as to form a slot between the distal end of a bow tie element and said ground plane; and,

a lossy resistive material adjacent said slot and removed from the center of said antenna to lower the VSWR of the antenna across its bandwidth and to minimize nulls in the antenna pattern of said antenna.

2. The antenna of Claim 1, wherein the bow tie antenna elements lie in a direction parallel to the plane of the ground plane, and further including at the distal end of each of said bow tie elements a downwardly-depending vertical plate, said vertical plate lowering the low frequency cutoff of said antenna.

3. The antenna of Claim 2, and further including a second bow tie antenna orthogonal to said first bow tie antenna, said second bow tie antenna having respective downwardly-depending vertical plates at the distal ends of the bow tie elements thereof, and further including a short between adjacent plates, thus to minimize cross-coupling between the bow tie antennas.

4. The antenna of Claim 1, and further including a second bow tie antenna coplanar with the first bow tie elements of said first-mentioned bow tie antenna and orthogonal thereto in a quad configuration.

5. The antenna of Claim 4, wherein adjacent edges of the bow tie elements of said first and second bow tie antennas define a slot.

6. The antenna of Claim 5, and further including an extension of said ground plane between adjacent edges of said bow tie elements.

7. The antenna of Claim 6, wherein said ground plane extension is wedge-shaped.

8. The antenna of Claim 1, wherein said lossy resistive material includes a ring of foam material underneath said slots.

9. The antenna of Claim 1, wherein said lossy resistive material includes a resistive sheet on top of a slot.

10. The antenna of Claim 1, wherein the points of said bow tie antenna define the center of said antenna and wherein the lossless slot length from the center of the antenna to said lossy resistive material is equal to or greater than ¼ the wavelength of said antenna at the highest frequency thereof.

11. A method for providing a broadband VSWR for a conformal, structurally-embedded broadband antenna, comprising:

providing the antenna with opposed bow tie elements having distal ends spaced from an adjacent ground plane so as to define a number of slots; and,

placing lossy resistive material at the slots to lower the VSWR of the antenna across the entire bandwidth thereof, said lossy resistive material also minimizing nulls in the antenna pattern at the high frequency end of the antenna.

12. The method of Claim 11, wherein said lossy resistive material is at a position adjacent a slot at which no antenna currents occur.

13. The method of Claim 11, and further including placing resistive sheets to bridge said slots, thus to aid in reducing the VSWR over the entire bandwidth of the antenna.

14. A method for decreasing the low frequency cutoff of a broadband, low-observable, conformal antenna embedded in a cavity and having orthogonally-oriented bow tie elements, comprising the step of electrically coupling to the distal end of the bow tie elements a downwardly-depending vertical plate, the plates serving to extend the effective size of the antenna at the low frequency end thereof.

15. The method of Claim 14, and further including the step of shorting adjacent vertical plates together, thus to provide capacitive loading to the cavity and further reduce the resonant frequency of the bow tie and to suppress coupling between the bow tie elements.

16. The method of Claim 15, wherein the shorting is located at the distal end of adjacent vertical plates.

17. A method for creating broad bandwidth of a conformal cavity-embedded broadband antenna, comprising the step of utilizing opposed bow tie elements to make up the antenna, the bow tie elements defining slots between adjacent ones thereof.

18. The method of Claim 17, wherein the cavity-embedded bow tie elements have the distal ends thereof surrounded by a ground plane so as to define a number of slots between respective distal ends of bow tie elements and the ground plane; and locating lossy resistive material at the slots to reduce the VSWR of the antenna across the bow tie and stabilize radiation patterns.

19. The method of Claim 18, wherein the center of the antenna corresponds to the center corresponding to the meeting of the points of the bow ties thereof, and wherein the lossy resistive material is kept as far away as possible from the center of the antenna.

20. The method of Claim 19, wherein the lossless slot length between the center of the antenna and the lossy resistive material is equal to or greater than ¼ of the wavelength of the highest frequency of the receive band of the antenna, whereby the overall performance of the antenna is not impeded by the use of the lossy resistive material.

21. A broadband structurally-embedded conformal antenna, comprising:

a ground plane;

an aperture in the ground plane;

a cavity opened to said aperture and extending below said ground plane;

a bow tie antenna having bow tie elements located in said aperture, the distal ends of said bow tie elements spaced from said ground plane so as to form a slot between the distal end of a bow tie element and said ground plane, said bow tie antenna elements lying in a direction parallel to the plane of the ground plane; and,

a downwardly-depending vertical plate at the distal end of each of said bow tie elements, said vertical plate lowering the low frequency cutoff of said antenna

22. The antenna of Claim 21, wherein said plate is capacitively coupled to the adjacent bow tie element.

23. The antenna of Claim 21, and further including a second bow tie antenna orthogonal to said first bow tie antenna, said second bow tie antenna having respective downwardly-depending vertical plates at the distal ends of the bow tie elements thereof.

24. The antenna of Claim 21, and further including a second bow tie antenna coplanar with the first bow tie elements of said first-mentioned bow tie antenna and orthogonal thereto in a quad configuration.

25. The antenna of Claim 24, wherein adjacent edges of the bow tie elements of said first and second bow tie antennas define a slot.

26. A method for decreasing the low frequency cutoff of a broadband, low-observable, conformal antenna embedded in a cavity and having orthogonally-oriented bow tie elements, comprising the step of electrically coupling to the distal ends of the bow tie elements a downwardly-depending vertical plate, the plates serving to extend the effective size of the antenna at the low frequency end thereof.

27. The method of Claim 26, wherein the downwardly depending vertical plate is capacitively coupled to the adjacent bow tie element.

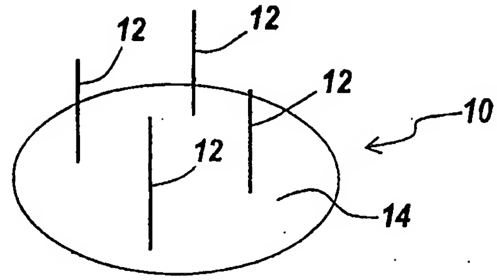


Fig. 1
(Prior Art)

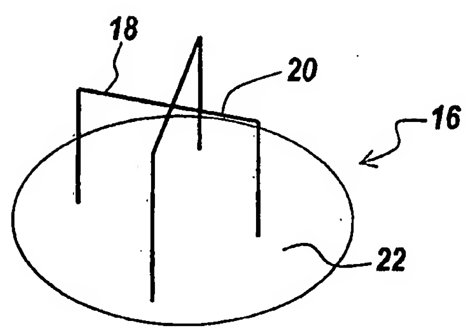


Fig. 2
(Prior Art)

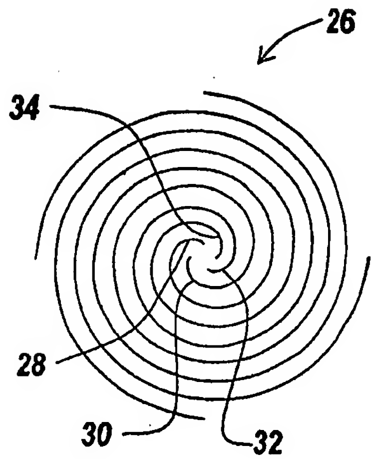


Fig. 3
(Prior Art)

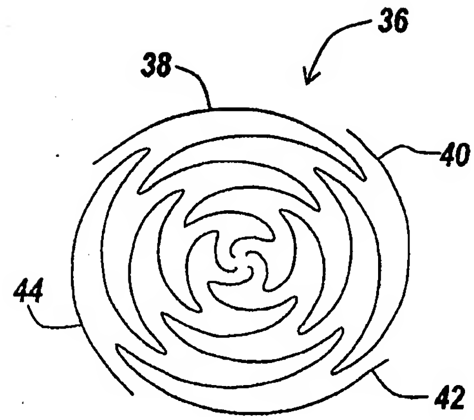


Fig. 4
(Prior Art)

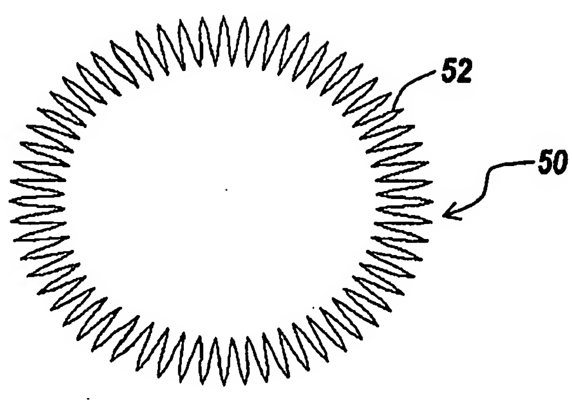


Fig. 5
(Prior Art)

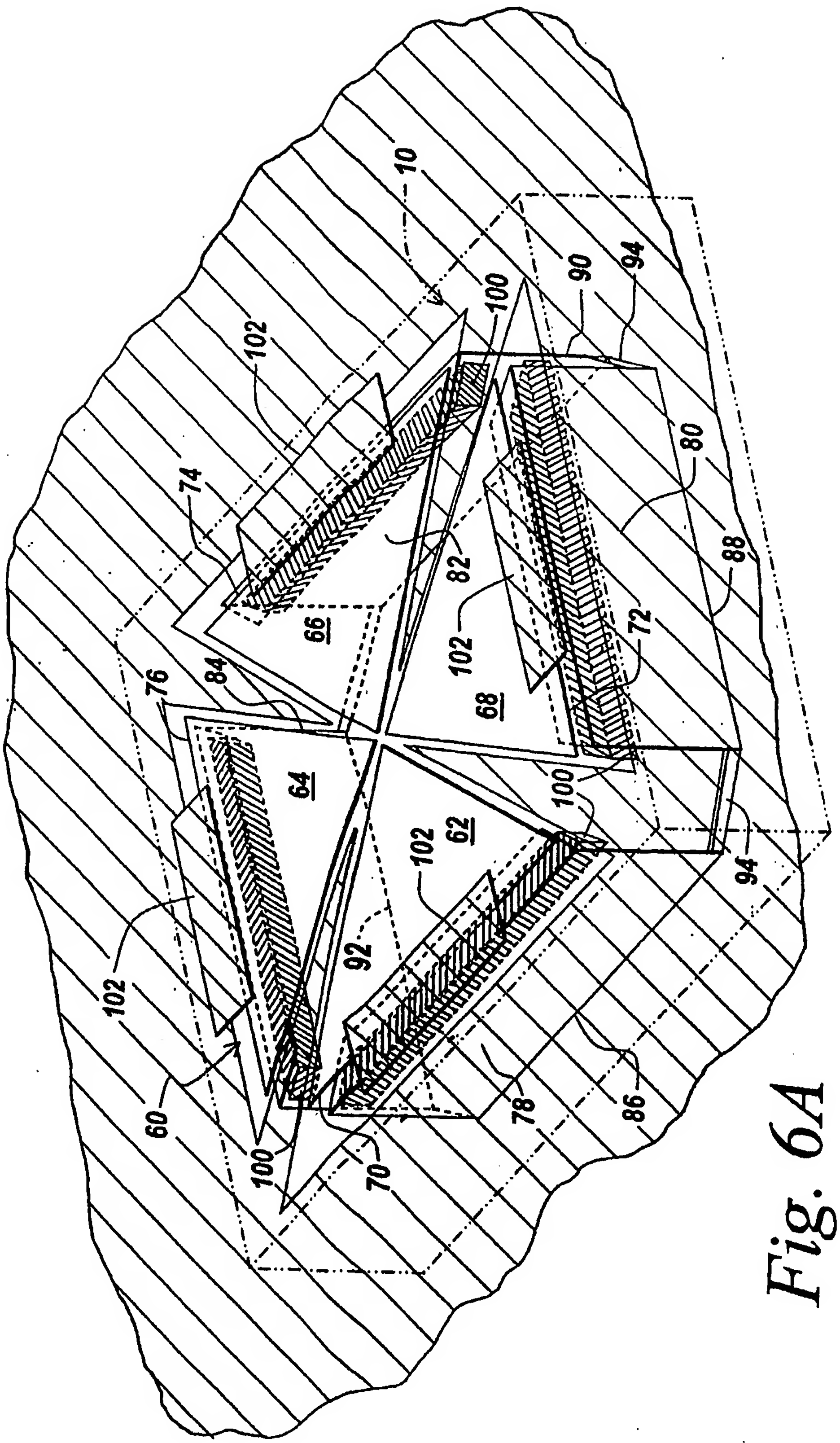


Fig. 6A

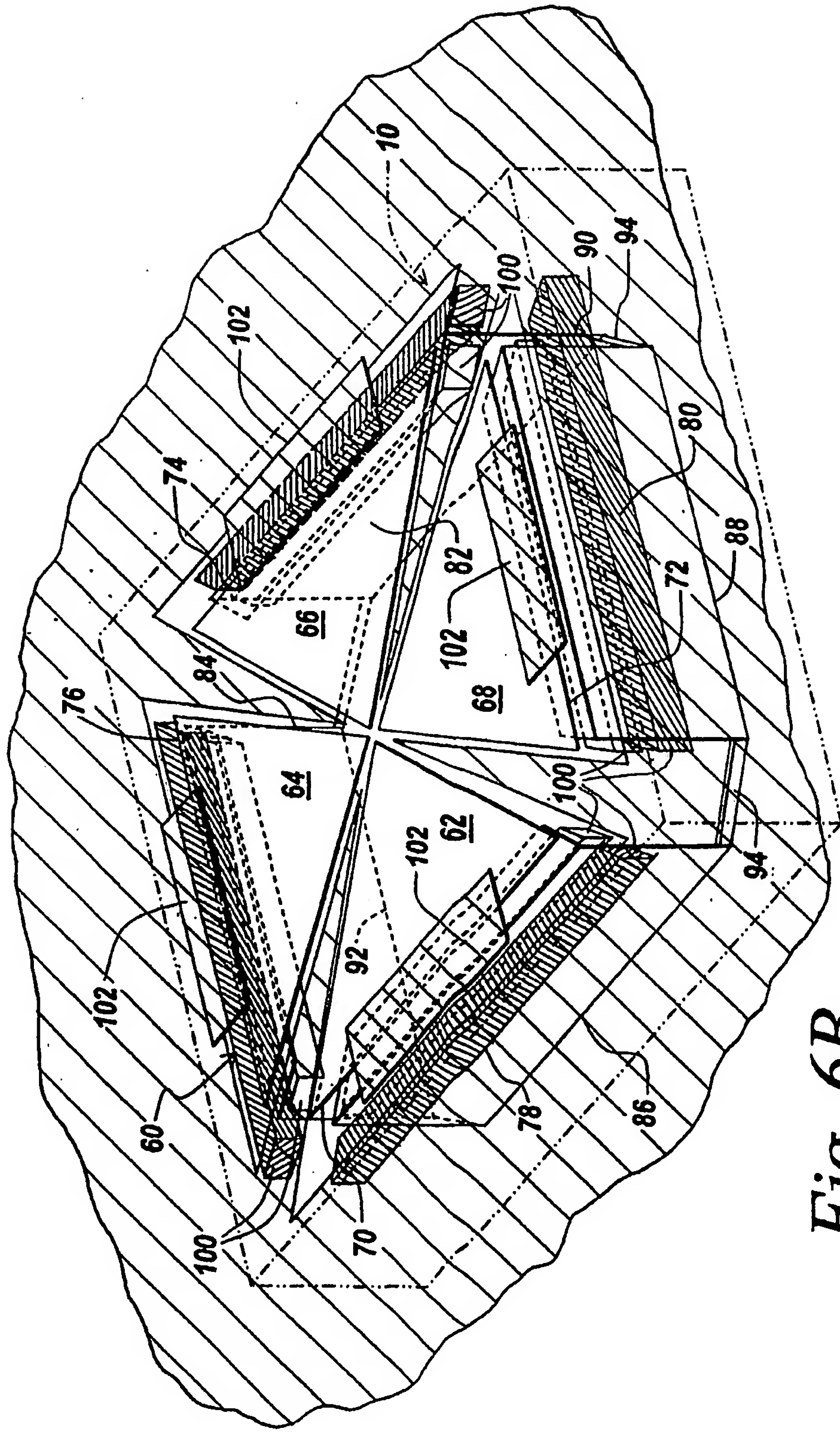

10
100
90
94
102
74
80
82
88
66
102
68
72
84
76
64
62
100
102
94
92
102
60
78
86
100
70

Fig. 6B

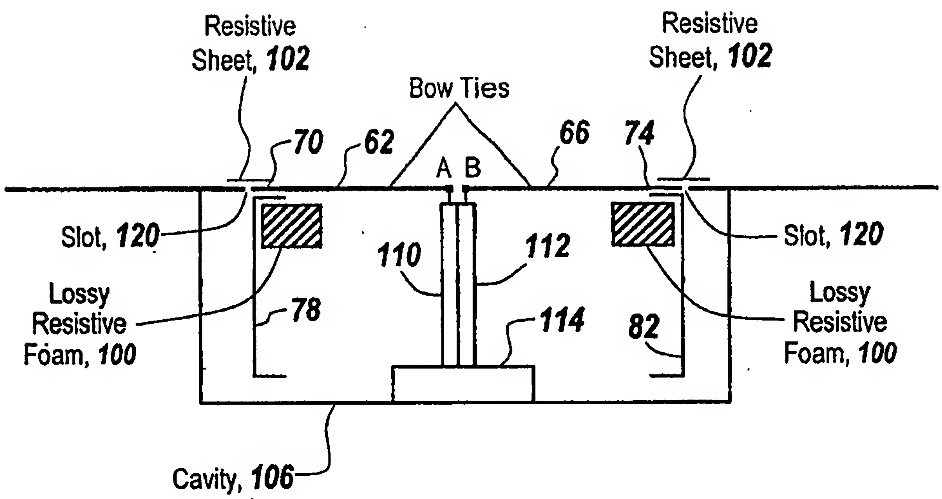

Resistive
Sheet, 102
Resistive
Sheet, 102
Bow Ties
70
62
66
74
A B
Slot, 120
Slot, 120
110
112
Lossy
Resistive
Foam, 100
78
114
82
Lossy
Resistive
Foam, 100
Cavity, 106

Fig. 7A

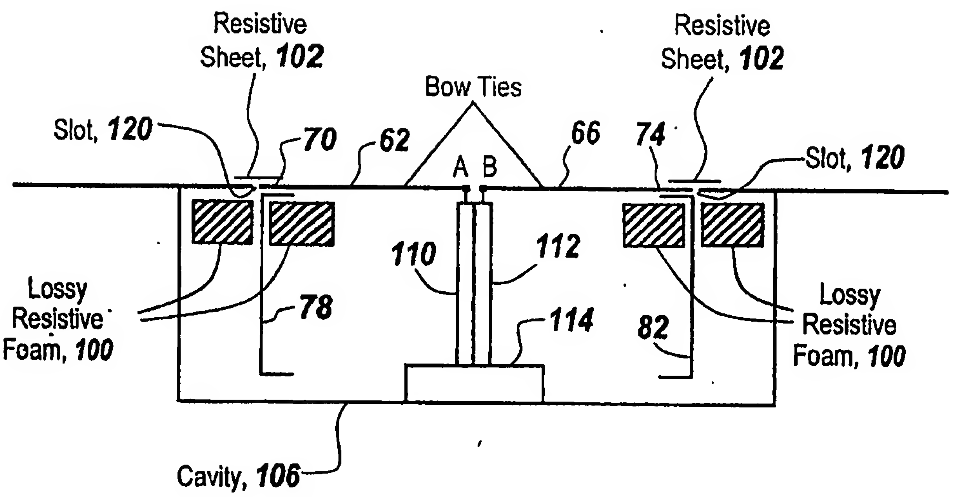

Resistive
Sheet, 102
Resistive
Sheet, 102
Bow Ties
Slot, 120
70
62
66
74
Slot, 120
A B
110
112
Lossy
Resistive
Foam, 100
78
114
82
Lossy
Resistive
Foam, 100
Cavity, 106

Fig. 7B

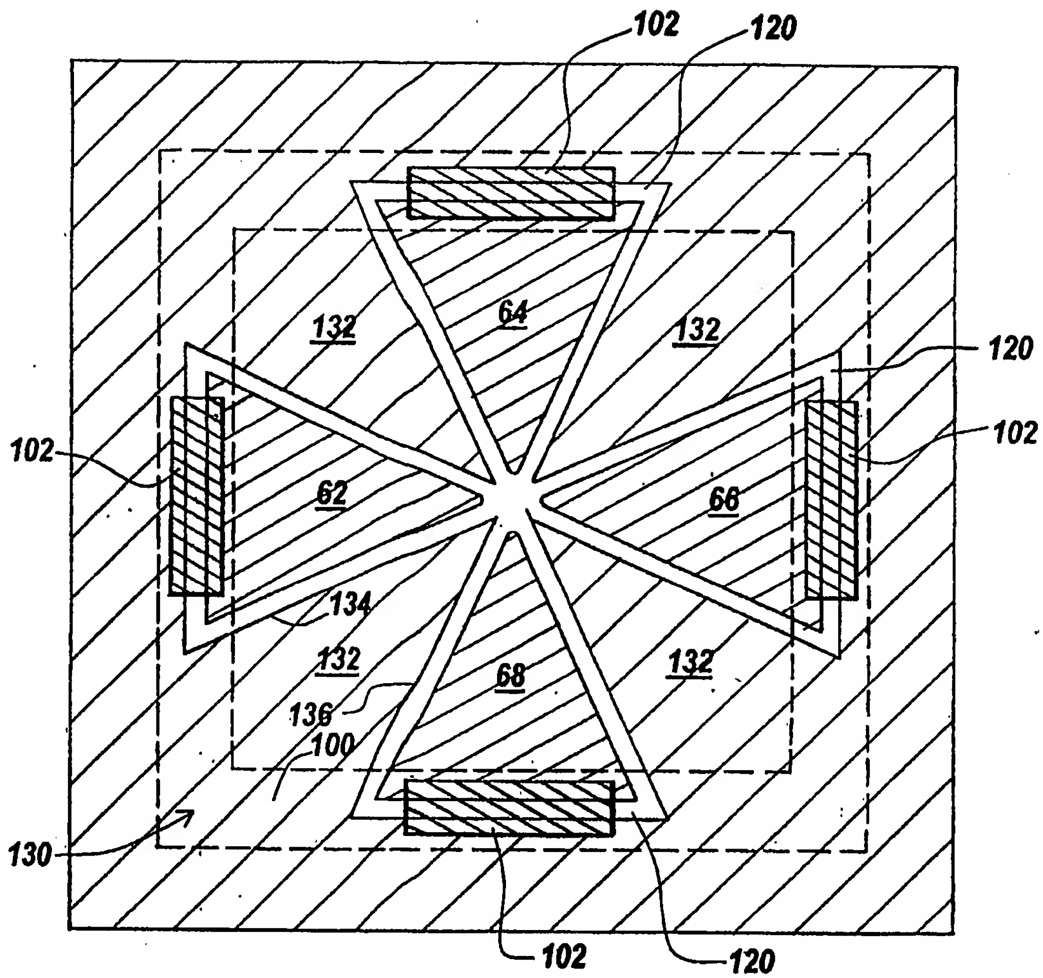
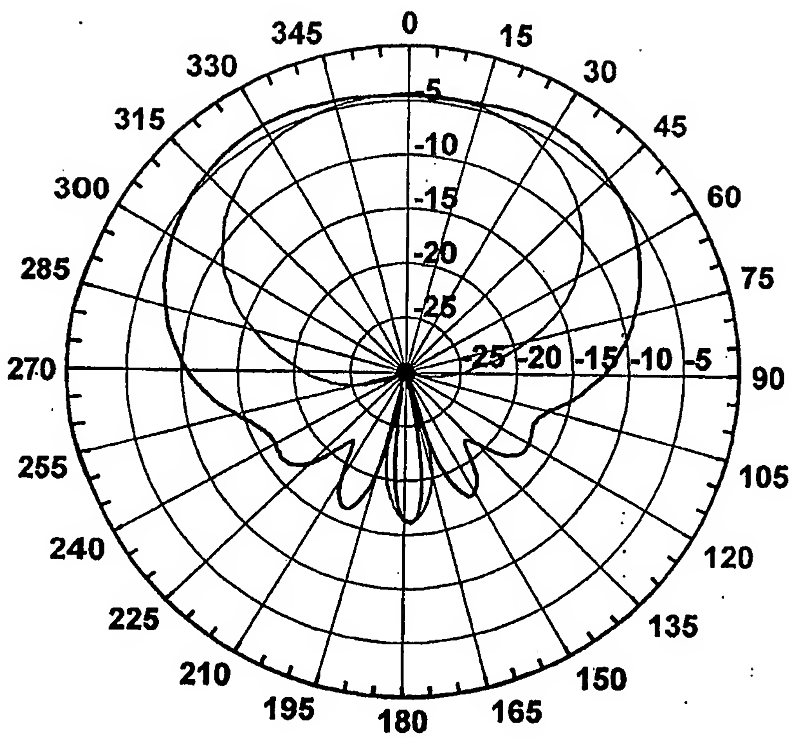

102
120
132
64
132
120
102
102
62
66
134
132
68
132
136
100
130
102
120

Fig. 8


0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
-5
-10
-15
-20
-25
-25 -20 -15 -10 -5

300 MHz

Fig. 9

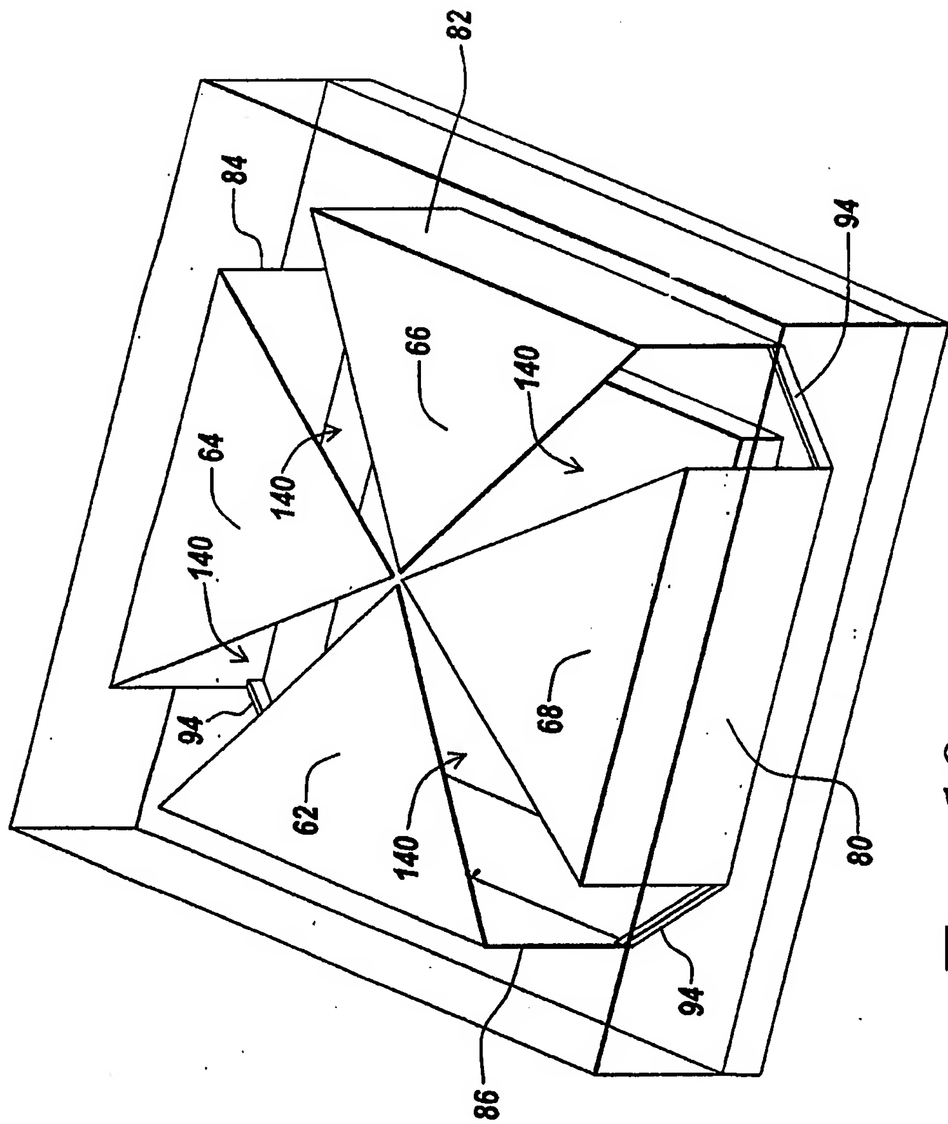


Fig. 10